MARS PATHFINDER MICROROVER FLIGHT EXPERIMENT - A PARADIGM FOR VERY LOW-COST SPACECRAFT'

I AA-L-0506

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Abstract

The Mars Pathfinder Microrover Flight Experiment (MFEX) will be carried by the Mars Pathfinder mission to the surface of Mars, where it will perform technology, science and Mars mission engineering experiments in July 1997. The total cost of MFEX, including H/W and S/W development, mission design, operations and inflation is $25M, but it will perform many of the functions of large rovers estimated to cost over $1 B.

The Mars Pathfinder microrover packs full planetary spacecraft functionality into a very small package (<12 kg, <0.1 cubic meter, <$25M cost). It is self contained (solar powered, with primary batteries for night operations and emergencies); it takes pictures (with 3 cameras); carries and supports a science instrument (an Alpha-Proton-X-Ray spectrometer); performs technology experiments (e.g. for soil mechanics and small vehicle mobility in an unknown terrain); is commanded; collects, stores, packetizes and downlinks data; monitors and controls its attitude and autonomously navigates; actively manages its power and its thermal control; and telecommunicates. In addition it functions on the Martian surface, a much harsher environment than most spacecraft must face. On top of that, the microrover must interact with and respond to its environment in an "intelligent" fashion to carry out its mission and avoid hazards in an uncertain terrain, rather than merely exercising preprogrammed sequences as an ordinary spacecraft does.

The factors which allow this include: 1) use of a new onboard autonomous "behavior control" technique (first developed at MIT) combined with "Computer Aided Remote Driving" (developed at JPL); 2) the world-wide miniaturization of electronic and mechanical components; 3) the development at JPL of the a 6-wheeled, very mobile "rocker bogie" mobility system; 4) functional support by the Mars Pathfinder mission (the rover is delivered by, and communicates with earth through, the Mars lander, requiring a rover-lander communication range of less than a kilometer - a large rover power and mass savings); 5) relatively modest mission requirements (the rover carries only one instrument and must survive only for a few months in space and from a week to a month on the Martian surface); and 6) innovative management techniques"

The Mission

Mars Pathfinder will be launched on a Delta 2 launch vehicle, and the Pathfinder spacecraft will provide support services to the rover from launch through landing. The rover is stowed on one of the petals of the tetrahedral shaped Pathfinderlander petals. Pathfinder will fly directly to Mars, enter the atmosphere and land with the aid of parachutes solid rockets and airbags. After landing the lander will open, positioning its petals so that solar energy can be collected and the rover is poised for

' The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

deployment.

The lander camera will take a panoramic image of the surroundings and transmit it directly to the earth at about 1-5 kilobits per second. The rover will be released by the lander and will erect itself and move down deployment ramps to the surface. It is thereafter independent except for using the lander data and communications functions for command and telemetry.

The rover has three primary mission objectives:
1. Technology Experiments
2. Science Experiments
3. Mission Experiments

The technology experiments are to determine microrover performance in the poorly understood Martian terrain, Technology information is collected by instrumenting the rover mechanisms to determine wheel-soil interactions, detect hazards, determine navigational errors, etc. Because the rover is part of the Mars Pathfinder payload it will also gather science data by deploying an alpha-proton-x-ray spectrometer (APXS) against one or more rocks, and possibly soil, Finally, because Mars Pathfinder is an engineering test of a transport and landing system for Network, the rover will image the lander to allow its condition to be assessed,

Both the lander and the rover have limited redundancy and the thermal environment of the Martian surface is very harsh (O to -1 OO°C daily cycles). So the surface mission design must achieve the important mission objectives in a relatively short time (goal = 7 days). The lander-to-earth direct communications link is limited to about 5-6 kilobits per second, even using a lander high gain antenna, and therefore information to re-direct the rover can usually only be gathered after a whole sol's transmission. (A "sol" is a Martian day and is about the length of an earth day). Consequently the rover may only be commanded once per day, although capability to make minor command updates more than once per day is being included in the mission operations system.

Surface mission design is by scenarios, with timelines built around data transmission capabilities from the lander to earth. Scenarios are used as an integral part of the rover design process and were used, for instance, to determine that considerable on-board autonomy is required to accomplish mission objectives in a reasonable period of time. A baseline scenario has been constructed for planning the data transmission and storage requirements for both the lander and rover. Table 1 lists the major activities of the mission during the first 4 SOIS, showing that the rover's minimal objectives can be accomplished in this short time, if conditions are nominal.

In this nominal scenario the rover is deployed on the first sol, following lander opening and airbag retraction, plus transmission of the Entry Descent and Landing (EDL) data, and enough of the lander camera (IMP) panorama to safely deploy the rover. The rover may only travel far enough from the lander to image the lander, do a set of technology experiments, and put the APXS on the soil. The first one or two APXS spectra are taken overnight, to conserve the daylight hours for rover movement. The overnight spectrum will be powered by the rover's batteries.

The second sol is consumed directing the rover toward the selected rock, performing technology experiments on the way (assuming that a rock is close enough to be reached in two SOIS). The rover images the rock on the second sol. The third sol allows the rover to contact the rock and place the APXS on it, collecting the rock spectrum overnight. The rover position will be determined relative to the target at the end of each sol by imaging it from the lander.

Table 1
MARS PATHFINDER SURFACE ACTIVITY HIGHLIGHTS

Event	sol	Mars Surface Time hh:mm	Time after landing hrs	min
Land	1	3:14	o	o
Airbag retraction	1	3:59	0	46
1st Earth rise, 20º	1	4:13	1	0
Petal Opening (possible carrier link)	1	4:44	1	3
Establish comm with Earth, elev=55º, LGA at 40 b/s, DSS43	1	6:53	3	45
Ist Sunrise, 20º	1	7:08	4	0
Complete downlink EDL telemetry	1	7:53	4	46
Establish 1st comm on HGA, data rate=l 260 b/s, DSS43	1	8:47	5	42
Complete downlink panorama portion for rover deploy	1	10:23	7	20
Establish accurate comm on HGA, data rate=5530 b/s, DSS43	1	12:37	9	38
Complete downlink IMP pre-deploy panorama	1	13:28	10	30
Deploy Rover	1	13:29	10	31
Rover image of lander	1	13:44	10	47
Rover image of soil	1	13:56	10	59
APXS on soil	1	14:03	11	6
Complete downlink rover image of soil	1	14:03	11	6
1st Earth set, 20º	1	14:11	11	15
1st Sunset, 20º	1	16:51	13	59
Rover image of rock	2	11:28	33	7
Complete downlink rover image of rock	2	11:44	33	23
Complete downlink IMP post-deploy planning panorama	2	12:40	34	21
Complete downlink rover image of lander	2	12:42	34	23
Complete downlink APXS soil data	2	12:43	34	24
APXS on rock	3	10:20	56	36
Complete downlink APXS rock data	4	7:26	78	17
Complete rover technology experiments (finish rock APXS)	4	7:26	78	17
Complete lander primary mission objective (end of sol 4 downlink)	4	14:11	85	13

The full mission scenario includes two or three lander images and multiple APXS measurements and technology experiments, all within about 10 meters of the lander (within the highest resolution lander images) and requires about 7 SOIS. For the extended mission the rover can be risked on longer traverses. It can even head “over the horizon” (out of range of the lander’s camera) by using its own images for navigation.

The rover is controlled by an earth operator who views a work station with a stereo display of the lander’s (or rover’s) image of the terrain through 3-D glasses. The work station’s software allows an icon of the rover to be placed in the scene and the coordinates of this placement determined. These coordinates form the basis of the rover traverse commands. Commands which enable rover tasks, e.g. "perform a soil mechanics experiment", "place the APXS on a rock", are interspersed with traverse commands and sent to the rover through the Mars Pathfinder Mission Operations System (MOS). The commands are sent, shortly after sun and earth rise on Mars, to the lander, which forwards the commands to the rover over the UHF link, and the rover stores them for execution. Rover telemetry, including images, is stored, compressed and packetized on the rover. The rover notifies the lander when it is ready to transmit, and the lander o.k.'s transmission when it is ready to receive. Telemetry packets are downlinked over the rover-to-lander UHF link and the lander stores the packets for transmission to earth.

The Rover Design

A mix of new and old technology has been employed. The autonomous control and navigation system, mobility system, thermal control system and power switching scheme have all been invented for MFEX, building on the NASA telerobotics and rover technology programs. The electronic parts are primarily space qualified (Class B). On the other hand, MFEX also makes extensive use of commercial components (e.g. UHF modems, power converters, motors), and has created new processes for qualifying them for space application.

The rover has an anticipated mobile mass of 9.0 kg, science instruments add about 2 kg, and another 5.0 kg is allocated for lander-mounted rover equipment. These limits are dictated by the payload capability of the Mars spacecraft. While the rover has a nominal height of 280 mm (with 130 mm ground clearance), the available lander volume allows only 200 mm, forcing the rover to stow at a static height of 180 mm. The rover is 630 mm long by 480 mm wide. This small size poses considerable challenges for mobility, computation, thermal control, power and telecommunications.

The rover configuration is shown. in Figure 1. Mobility is by a 6-wheeled "rocker-bogie" chassis, with all wheels driven, and with the front and rear sets of wheels being steered. Although the rover can move through very hazardous terrain relative to its size, it is a very stable platform (when compared to more conventional three body designs) for science, imaging and proximity sensing. For obstacles which it can't surmount, the rover will depend on its on-board sensing and autonomous control system to find a safe path around them to reach the operator-designated target.

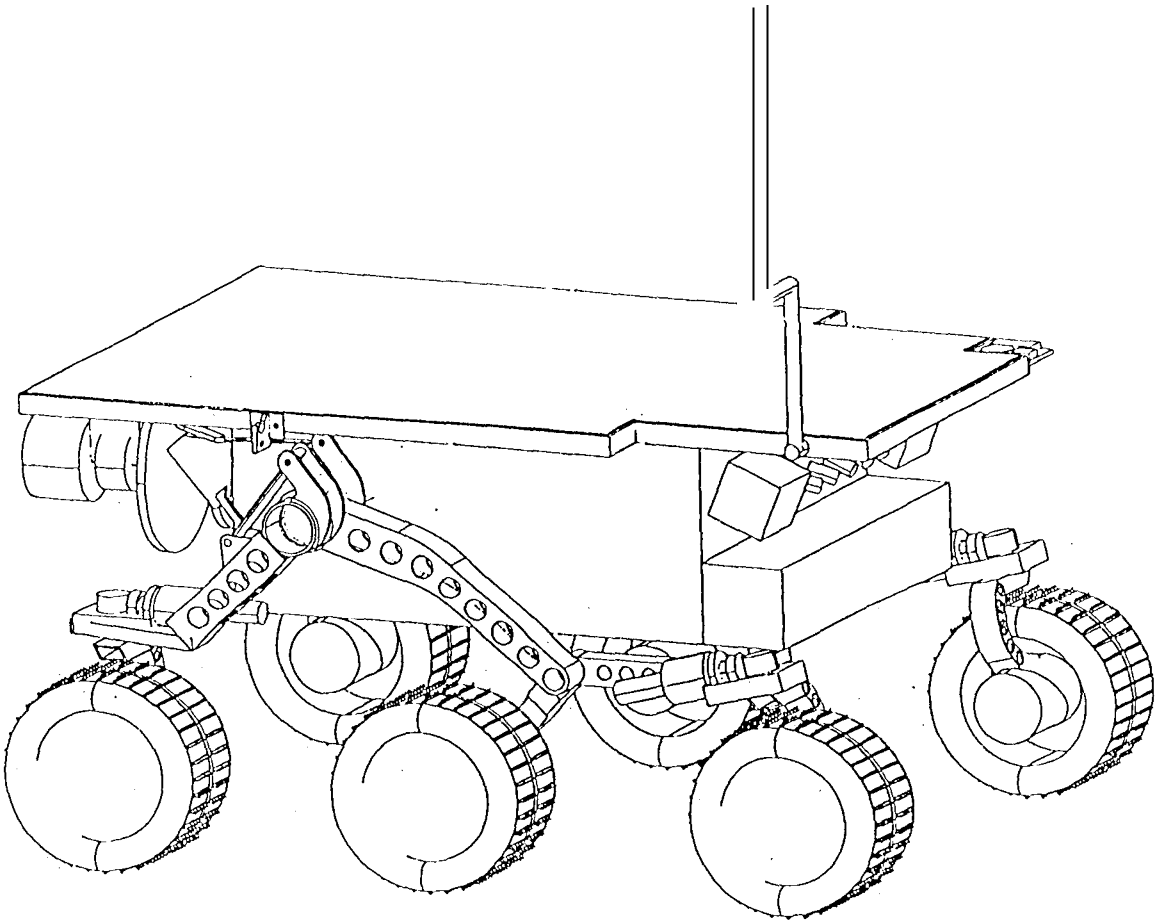
All on-board computing and control functions will be handled by a single Intel 80C85 processor, selected for its low cost and radiation/heavy particle resistance. This is only an 8-bit processor which runs at about 100 kips, in contrast to new technology flight processors. However, development to date indicates that it is ample for the rover's needs, provided that rover speeds remain slow. (It is also vastly superior to all computers used by planetary spacecraft before Galileo).

CPU, 1/0 and power boards are being designed which can be cheaply manufactured in flight qualified technology, and in a small, low power package. The processor and I/O board form a computer which will perform all the computational functions of the rover, from command decoding, to sensor data collection, to control response calculations, to telemetry collection and packetizing. All elements of the computational system are Single Event Latchup (SEL) resistant.

A new proximity sensing technology which was developed by an OACT technology program is baselined for MFEX. This utilizes the central processor to read out images from commercial charged couple devices (CCD's). This system uses ranging information from commercial laser light stripers to identify obstacles, such as large rocks, overhangs and holes. Then autonomous hazard avoidance “behaviors” will drive the rover around the obstacle. Other sensors are also used for hazard avoidance, health monitoring, and navigation dead reckoning.

Figure 1

MICROROVER CONFIGURATION



Rover telecommunications will be by means of commercial, half duplex, UHF modems operating at about 460 MHz and broadcasting over 1 meter-high whip antennas. One modem/antenna is located on the rover, the other on the lander. The lander data system interface with the modem is through an RS 232 port for simplicity. The modems, currently being procured, are from the Motorola R-Net series, which is low power and Mil-Standard qualified. Communication is possible over several hundred meters, even if the rover goes “over the horizon” from the lander’s view. A new JPL “Class D“ parts qualification process is being developed using the Motorola modem as a test case.

Rover power is provided by 0.25 square meters of solar array. This is sufficient to power the rover for several hours per sol, even in the worst conditions of atmospheric dust. Nominal peak power is 16.4 watts. The array cells are space qualified Gallium Arsenide, and will be purchased in a common buy with the lander solar arrays for cost savings. As a backup and augmentation, 150 MW of primary D-cell batteries (Lithium Thionyl Chloride cells developed at JPL), will be enclosed in a thermally insulated compartment called the Warm Equipment Box, or WEB, which features a new, very efficient thermal design being patented by JPL.

Power control is relatively complex. The use of a variety of cheaply obtained commercial, flight and Mil-Standard parts means that regulated power at a number of voltage levels is required. Power is managed to maximize power margin and simplify system design. All power switching is controlled by the central computer. A sophisticated "wake-up" scheme has been designed into the power system to ensure that the computer "wakes up" only when there is sufficient solar energy to support it without brownout, although nighttime operations can be supported off the primary batteries.

Temperature sensitive elements (electronics and batteries) have been selected to be qualified to -40°C and will be enclosed in the Warm Equipment Box. Three RHU's will be installed in the axle of the rover inside the WEB. The WEB efficiency, plus the RHU heating, is sufficient to maintain the WEB contents between ±40°C during both cruise and surface operations without requiring power to heat at night. Elements outside the WEB are being qualified to withstand Mars ambient surface temperatures.

MFEX Implementation

MFEX is an example of a "Better, Faster, Cheaper" NASA activity. Consequently the rover's design and new processes for implementing it are being developed concurrently. Figure 2 illustrates the implementation strategies being used.

The focus of the cost constrained activity is a deliberate constraint on computational power, coupledwith new autonomous control software technology and sensing/control architecture. Performance and risk are variables to achieve the costs constraints (for example, low-speed computing is enabled by slow rover speeds, and required by the lack of mass and power).

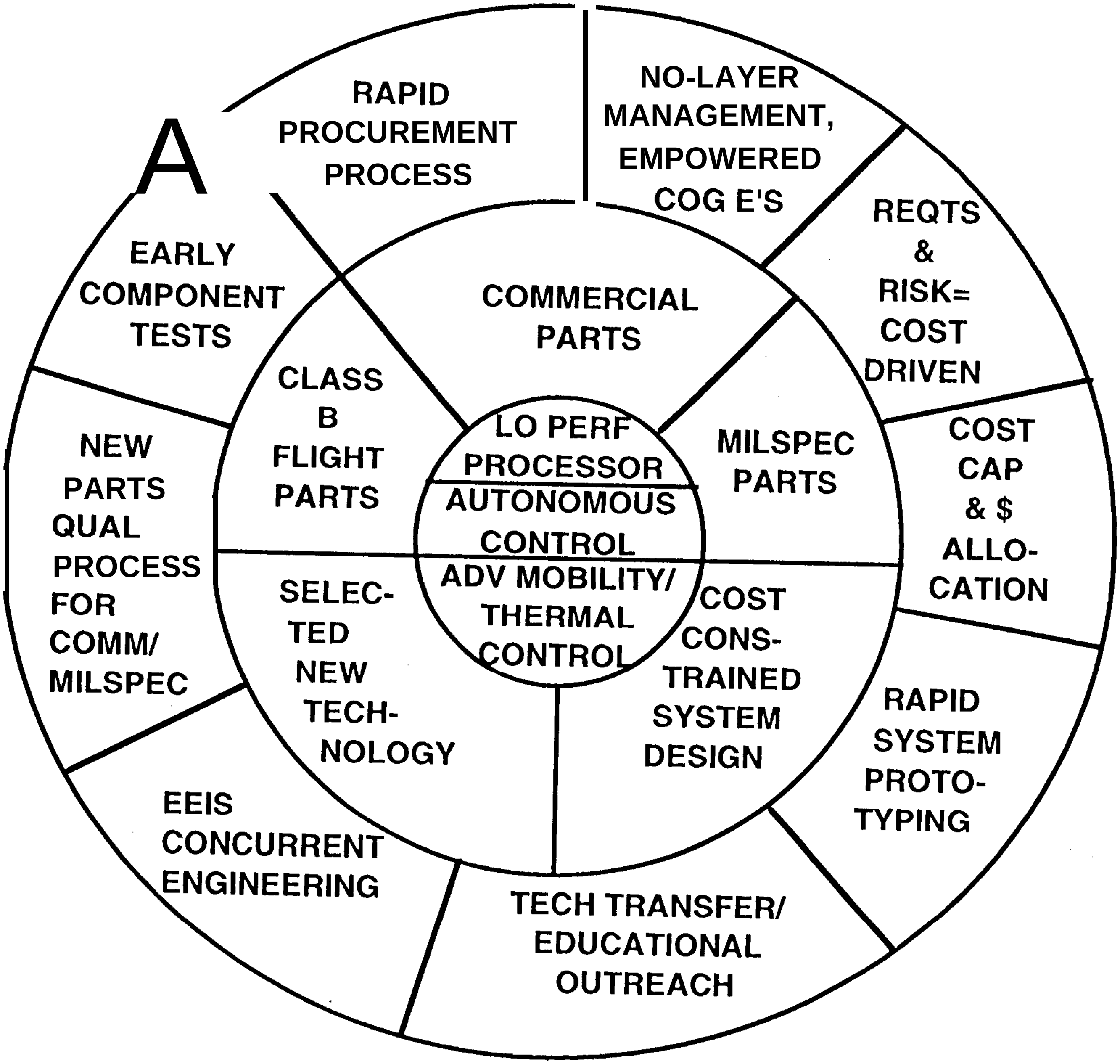
The selection of affordable parts and a cost-constrained design are built around the low performance computer and its advanced autonomous software. This includes the extensive use of low-cost (by space standards) commercial and Mil-standard components. Around that are wrapped cost effective processes: a small, low overhead team; rapid prototyping/concurrent engineering; new processes for parts qualification and procurement; and selected industrial participation for cost-effective technology transfer.

In order to meet the cost constraints, and since the mission duration is relatively short and the radiation environment relatively benign, the rover will take selected design risks, such as maximizing the use of off-the-shelf parts. New classification and qualification procedures are being developed at JPL to minimize the cost of using such parts. Space flight qualified parts are used where ever cost effective, e.g. the CPU and I/O board will be comprised of flight qualified, radiation hardened parts. Block redundancy (multiple units of a component) is practically nonexistent, but considerable functional redundancy is used, e.g. solar panels and primary batteries back each other up.

As part of the low-cost process for Mars Pathfinder the End-to-End information System (EEIS) is being developed using a concurrent engineering process. The rover operations development is an intimate part of this process and is the focus of the earliest Pathfinder EEIS design and test activities.

Figure 2

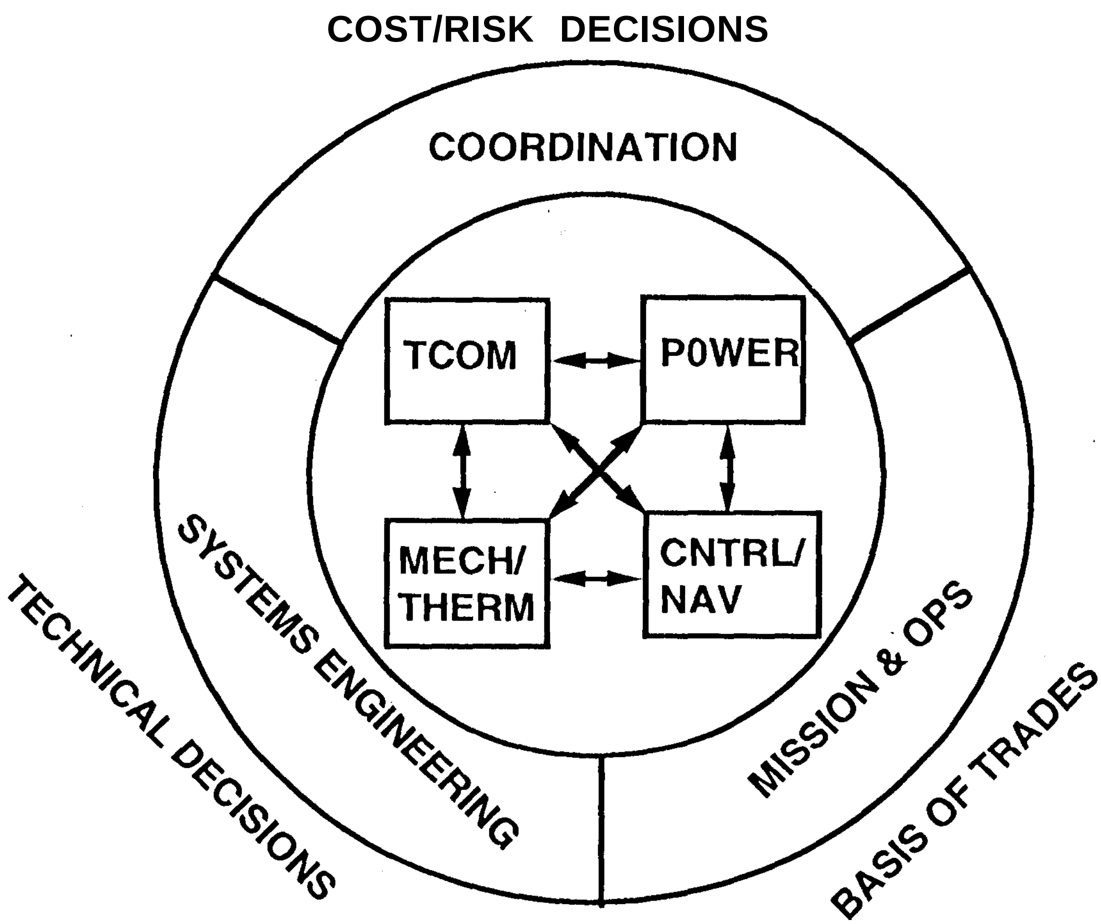
ROVER IMPLEMENTATION APPROACH



The MFEX team organization can be displayed hierarchically, but actually operates as shown in Figure 3. This type of structure has been likened to a “basketball team” as opposed to a “football team”. In a basketball team model the team responds quickly to changing situations, plays are planned in action by communication among the team rather than direction from a “quarterback”, and the team is small, (at its peak the rover team is 30 people strong).

Figure 3

MFEX ORGANIZATION - NEW BUSINESS STYLE



As illustrated in Figure 3 the functional Cognizant Engineers (for telecommunications, power, mechanical/thermal control, and control/navigation) control their own resources, under "contract" with the team leader. Detailed, day to day technical interactions occur directly between the Cog-E's. The MFEX team leader provides overall coordination with a focus on resource acquisition and allocation. When decisions on overall levels of risk are required the team leader makes them. On the other hand, when purely technical systems engineering decisions are required, they are usually made by the MFEX Chief Engineer, supported by his two person staff, and in conjunction with the functional Cog-E's. The Mission and Operations engineer develops the scenarios which are used as the basis of the system trades, and which provide the backbone for the rapid prototyping operational testing.

The MFEX activities are built around a rapid prototyping approach. "Rocky 4" was stripped to the bare chassis for mobility testing (Rocky 4.1) in sand and lunar simulant. Motors and mechanisms closer to flight were added for these tests, and then the chassis was given to the control subsystem. Control breadboarded a complete suite of sensors and a processor and I/O board, for use in software development (Rocky 4.2). With yet another set of motors and gears Rocky 4.3 is now operating under software control in a sandbox and is being used as a software development tool. Rocky 4.4 will feature a prototype computer and power board which is a functionally and physically close to flight as commercial technology will allow.

In parallel with this system development, component selection and testing are proceeding. For example, commercial motors and gears are being evaluated in a small thermal-vacuum chamber for their resistance to frigid Martian conditions. The commercial Motorola modems and a few other electronic parts have been evaluated in a particle accelerator for their susceptibility to Single Event Latchup. The modems do indeed latch, although an occurrence during the short mission is unlikely, however, they do not fail during latchup, and recover if power cycled. The rover and lander hardware and software design have been modified to provide circuit protection by power cycling if latchup occurs.

These rapid prototyping activities have been facilitated by a new rapid procurement process developed by JPL's procurement organization to support the "Better, Faster, Cheaper" way of doing business. This process allows one or two-day turnaround of small procurements for the engineering models. For larger procurements MFEX is utilizing a streamlined procurement process developed for the Mars Pathfinder Project.

The next step in the rapid prototyping process is to procure two sets of flight hardware, storing one set in clean conditions and using the other set to construct a "System Integration Model" or SIM. The SIM will be subjected to field and environmental testing, and will be used for interface checks with the Mars Pathfinder spacecraft during its Assembly, Test and Launch Operations (ATLO). Based on the SIM results the Flight Unit Rover (FUR) will be built up, perhaps with some modifications, in clean room conditions. This is more arduous than normal spacecraft cleanliness because of planetary protection restrictions. The Flight Unit will be integrated with the flight spacecraft and subjected to flight environmental testing in conjunction with the spacecraft.

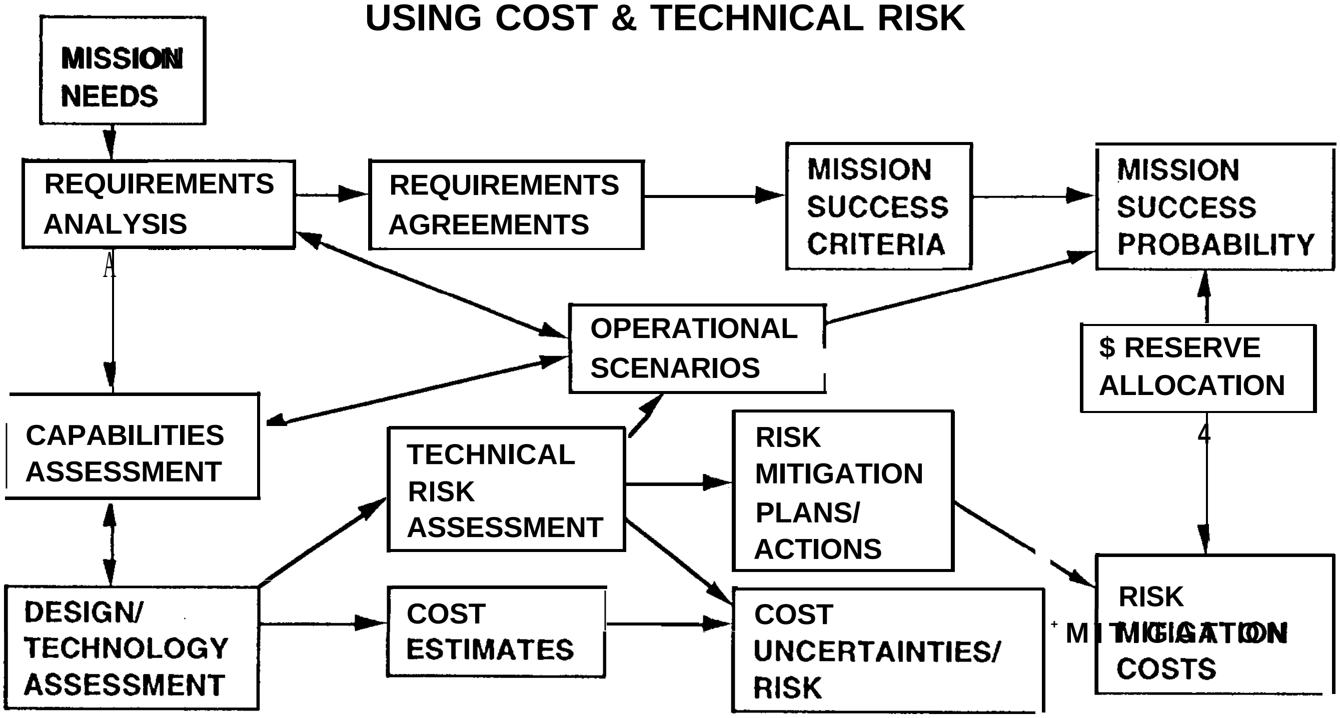
Cost, Risk and Performance Management

New approaches to cost estimation, risk management, and program control have all been used to ensure that the cost cap is not exceeded. MFEX is being conducted as a JPL in-house project because limited funding in the early years, plus the short project cycle and the relatively unproven technologies involved, prevent a system contracting approach. JPL's expertise in small rover R&D is being used to develop the prototypical Mars Pathfinder rover, which will lead to well-specified industry contracts for future rovers.

MFEX is conducting a Microrover Risk Assessment for NASA which includes developing a data base for determining the cost and effectiveness of technical risk mitigation measures taken by the Experiment. The risk assessment has defined a methodology for linking technical and cost risk, and linking these risks with the likelihood of mission success. Figure 4 shows a flow diagram of the process.

Figure 4

PROCESS FOR EVALUATING MISSION SUCCESS PROBABILITY USING COST & TECHNICAL RISK



The following example illustrates this process flow. The Mars Pathfinder Project defined mission needs for the rover of instrument deployment and imaging the lander to determine its condition. Originally the science desire was for the rover to deploy a Seismometer, and to carry an APXS and Neutron Spectrometer. The rover design capable of fitting within the cost cap was not capable of carrying the Seismometer which could be built (a mass problem). Also, the Mars science budget could not support the Neutron Spectrometer. Therefore, a capabilities assessment eliminated these two instruments, and the requirements analysis led to an agreement between the Mars Pathfinder Project and the Microrover Flight Experiment for the rover to carry only the APXS, placing it on rocks and soil. This requirements agreement was documented in the Mars Pathfinder Project Policies and Requirements Document and in the MFEX Implementation Plan.

Then the requirements analysis was refined, employing operational scenarios, to determine what APXS deployment capabilities could be achieved by the rover. Analysis of operational possibilities showed that a scientifically acceptable mission could be achieved within a few days, under nominal conditions. Therefore, a mission success criterion was derived that if one rock could be measured by the APXS the key science objective would be met. This mission success criterion has been accepted by the Project.

As part of the ongoing rover design process cost estimates were made so that agreements could be reached with the MFEX sponsor. Reserves have been provided in the cost estimates to cover both technical risk and cost risk. Technical risk assessments are ongoing, at increasing levels of detail. Potential failures were identified (e.g. the APXS might not be properly placed on the rock). Risk mitigation plans for the APXS deployment included designing and testing prototype deployment mechanisms, for which costs were estimated. Funds were allocated to implement this risk mitigation plan (i.e. to implement a "fail safe" mechanism which would retract the APXS from the soil in case of mechanism failure).

As the technical risk mitigation plans and actions are exercised, the cost uncertainties and risk are decreasing. MFEX is using an interview technique to determine what the Cognizant Engineers believe to be their riskiest tasks and how much cost risk is being incurred, As MFEX moves along and the design becomes better understood, the cost uncertainties are growing less. This information is used to predict "cost to complete". Part of planning for risk mitigation includes assessing the costs of risk mitigation, as well as the likelihood that cost estimates will be exceeded because of unpredictable factors. These assessments are used to allocate the $ reserves. Allocation of the reserves (and/or descope of performance) is made as problems are encountered, For instance, after testing the rover motors (an action in the risk mitigation plan), they were found to draw more power than predicted. options were assessed and additional reserves were allocated to cover costs of using better solar arrays to provide more 'power. At the same time the design was revised to be more power efficient, including moving even slower.

Operational scenarios used for assessing the technical risks and their impact on the probability of mission success. For example operational scenarios were used to evaluate the effect of slower rover travel on the achievement of other mission objectives, so the overall probability of mission success could be evaluated. Speed of rover operations was found to have little impact on accomplishment of objectives, but some design modifications were required to account for greater gyrocompass drift because of the longer traverse times.

With this information, management can determine, as development goes on, whether the likelihood of mission success is worth the mission cost.

Technology Transfer/Educational Outreach

Finally, MFEX is exploiting opportunities for technology transfer and educational outreach. Rover technologies are included in the Mars Pathfinder technology transfer plan. For example, a technology cooperation agreement is currently being developed with a small business to commercialize the rover mobility technology. The flight qualification of commercial technology is expected to open up opportunities for other low-cost space missions. And the rover thermal control technology may application to energy-efficient refrigerators.

The rover has been featured in several video productions for classroom education and has appeared in numerous publications of interest to the general public, including National Geographic, Road and Track and the Weekly Reader.

Overall, the lessons learned from MFEX are applicable to a whole class of low-cost space missions, especially Discovery and Small Explorer missions.